Battery Technology Advancements: Safe & Effective Applications

http://www.bbc.com/news/uk-england-manchester-29610570

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Vision

A non-profit, public-private partnership joining Industry, DoD/DoE, and Academia to rapidly develop, test, and commercialize the next generation of safe, reliable, and lightweight energy storage systems.

Distinguishing Features

1. Catalyze technologies by reducing long, expensive innovation-to-commercialization development cycle
2. Does not hold patent rights, reducing concerns to jointly develop
3. IP-secure, US-based facility generating reliable data using common techniques & equipment

Core Offerings

1. Low volume cell manufacturing
2. Full suite of Test & Evaluation capabilities
   - Cells -> Modules -> Packs -> Systems
   - Certification (UL, MIL, UN, SAE)
3. Applied Research & Consulting
   - Materials, process, safety, facilities, BMS, and integrated systems
   - Competitive analysis

Battery Technology Advancements:

Safe & Effective Applications

- Energy Storage Technology Landscape
- Batteries 101
- Battery Safety & Standards
- Ideal Applications Today
- Market Growth: Past, Present, and Future

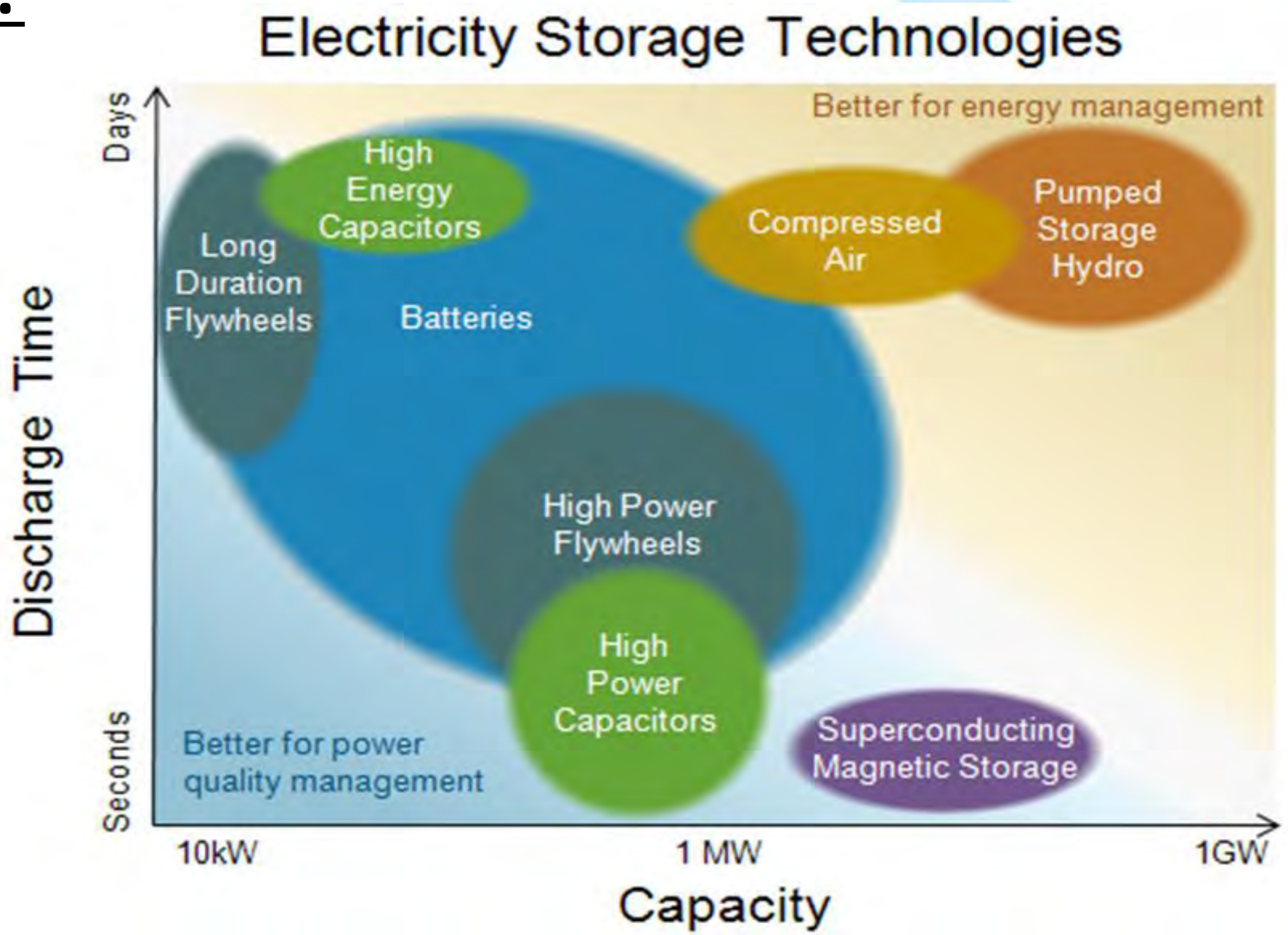
Energy Storage Technology Landscape

Why So Many Ways to Store?

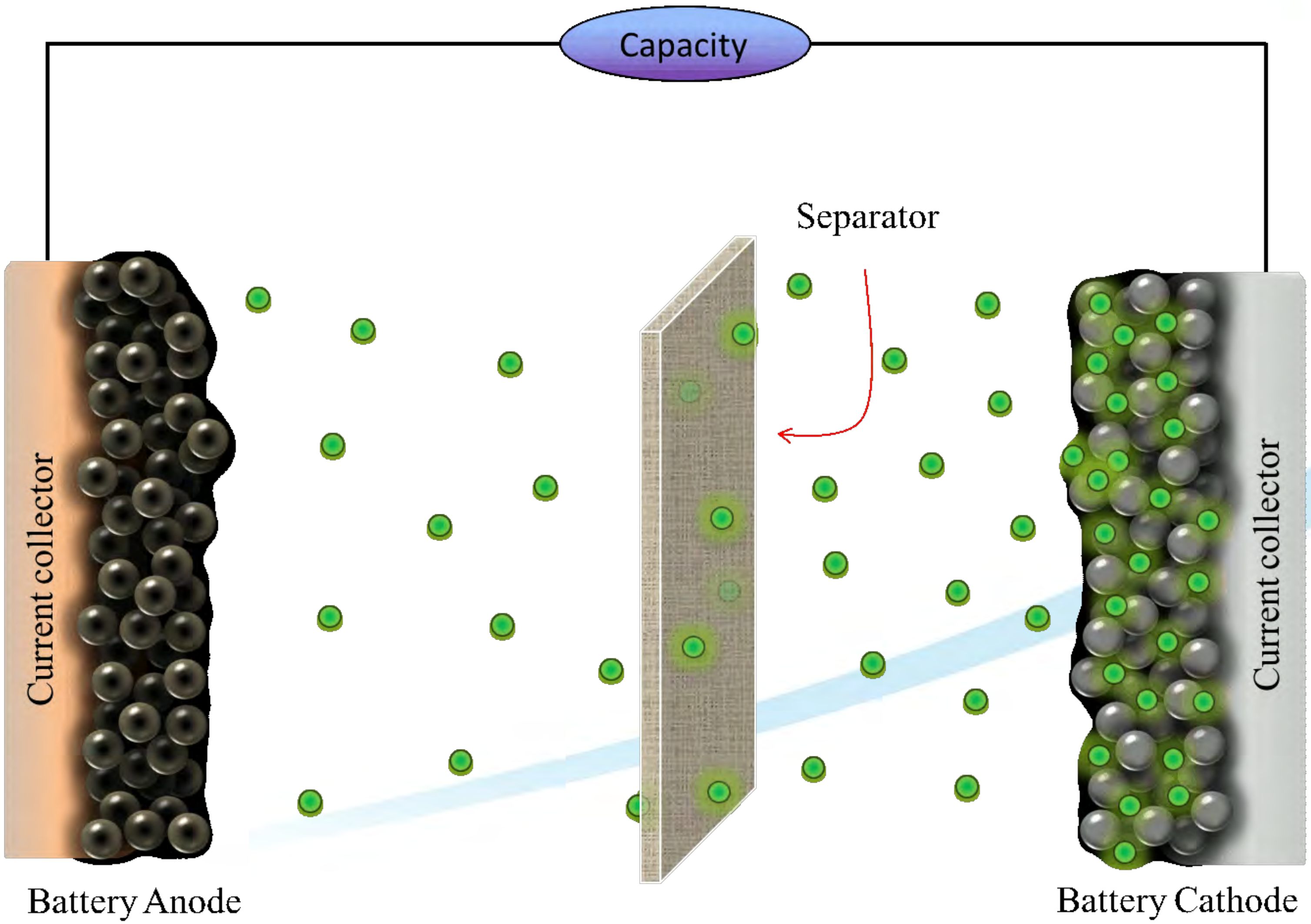
- Natural resources
- Application requirements
  - stationary v. mobile?
  - backup v. peak demand v. renewable?
- Technological advancements

Why Focus on Batteries?

- Well known manufacturing
- Flexible format
- Flexible technical performance
- Mobile and can be stable

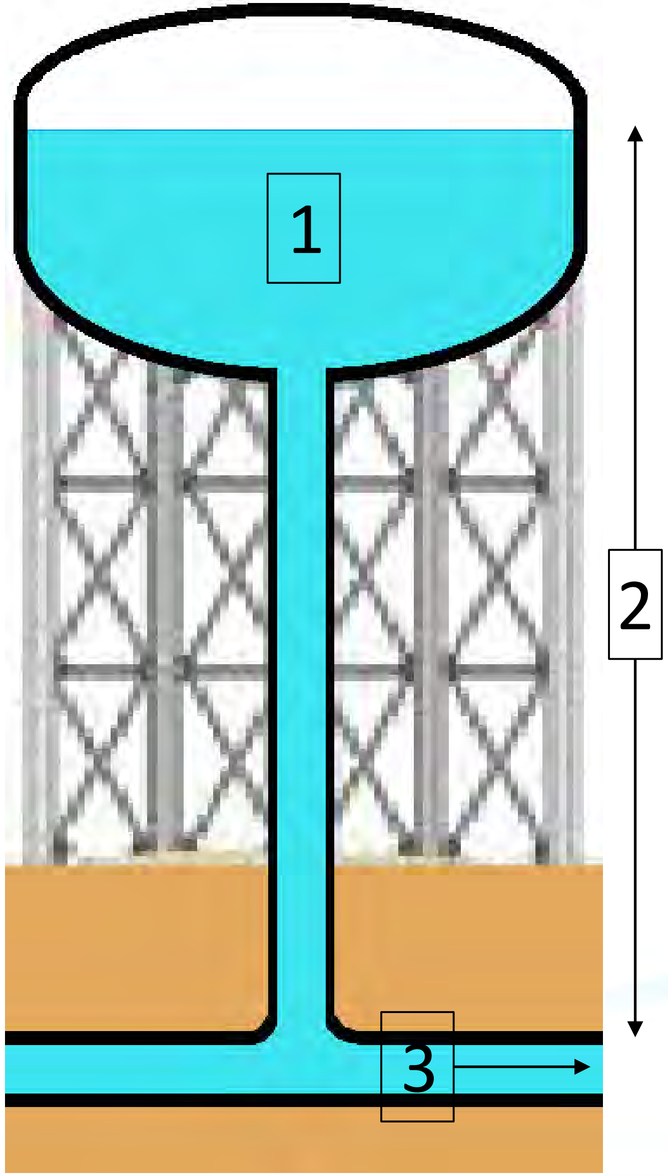


Batteries 101: The Cell



$$Li^{+} + e^{-} \leftrightarrow Li$$

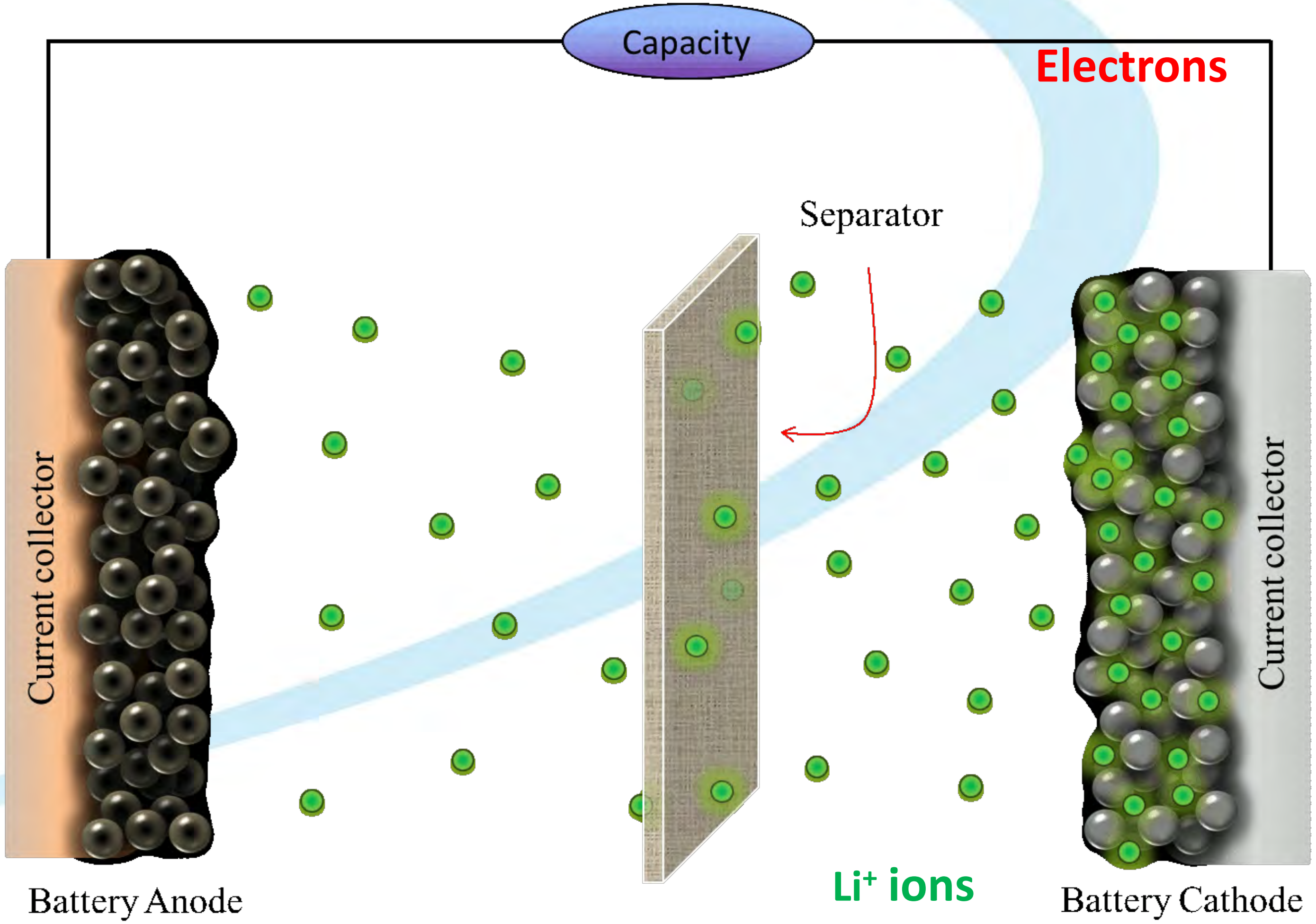
The Water Analogy…

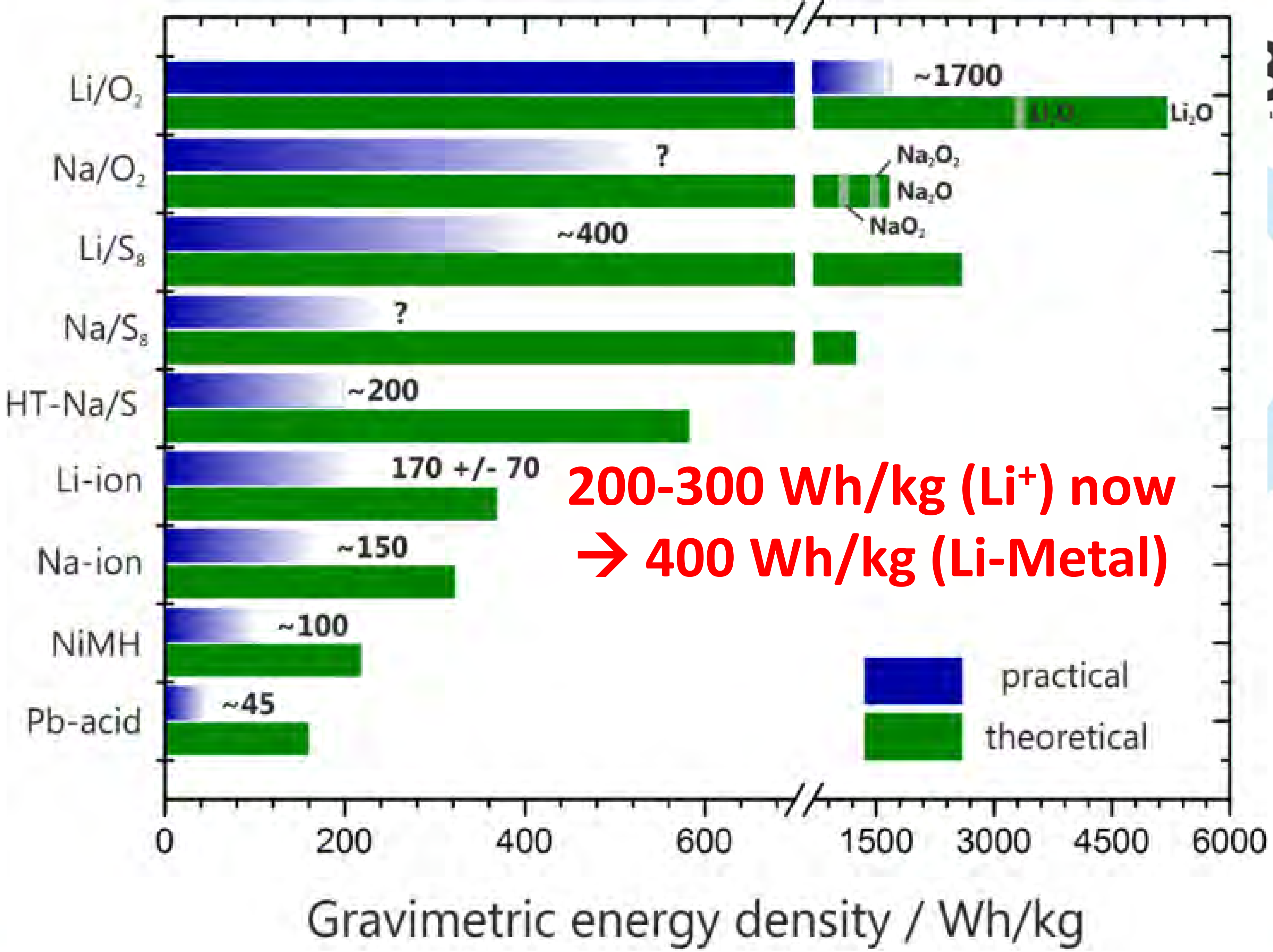


1. The total amount of water stored in the tower → **Capacity (Ahr)**
2. The height of the reservoir determines its potential energy relative to the ground → **Voltage (V)**
3. The flow rate of the water out → **Current (A)**
   a) Large diameter pipes → low resistance
      → **Power (W) (V x A = P)**

Cells: A Nano-Machine

- **Electron conduction**
  - Current collector & circuit
  - Active material (AM)
  - Conducting matrix holding AM
- **Li^+ conduction/polarization**
  - Separator
  - Electrolyte
  - Electrode porosity
  - Active material
  - SEI (Solid Electrolyte Interphase)
- **Other concerns (#1: HEAT)**
  - Volume change due to lithiation
  - Irreversible reactions
  - Coulombic vs. Energy efficiency

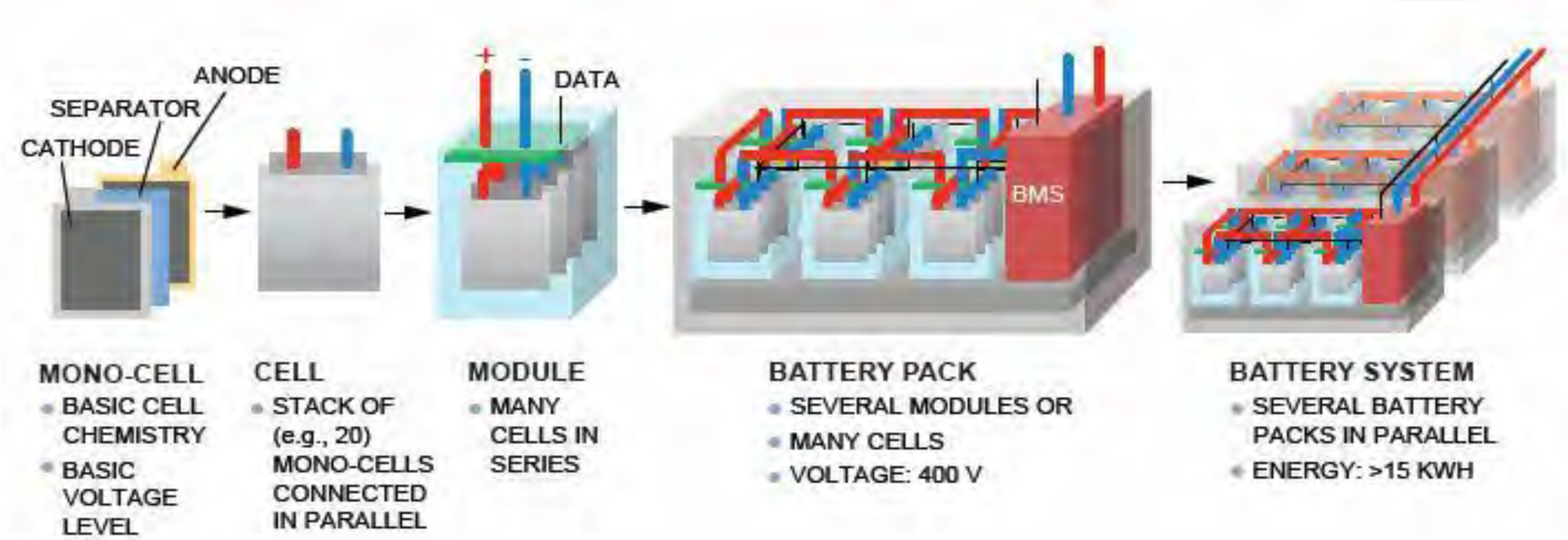




200-300 Wh/kg (Li^+) now
→ 400 Wh/kg (Li-Metal)

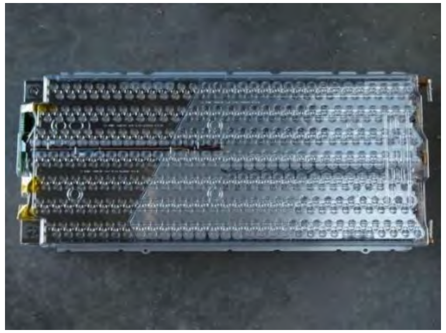
http://www.extremetech.com/mobile/217191-new-lithium-air-battery-could-drive-huge-performance-gains

Batteries 101: Modules, Packs, and Systems



Module Examples

6S/74P Tesla Module
(444 18650 Cells)



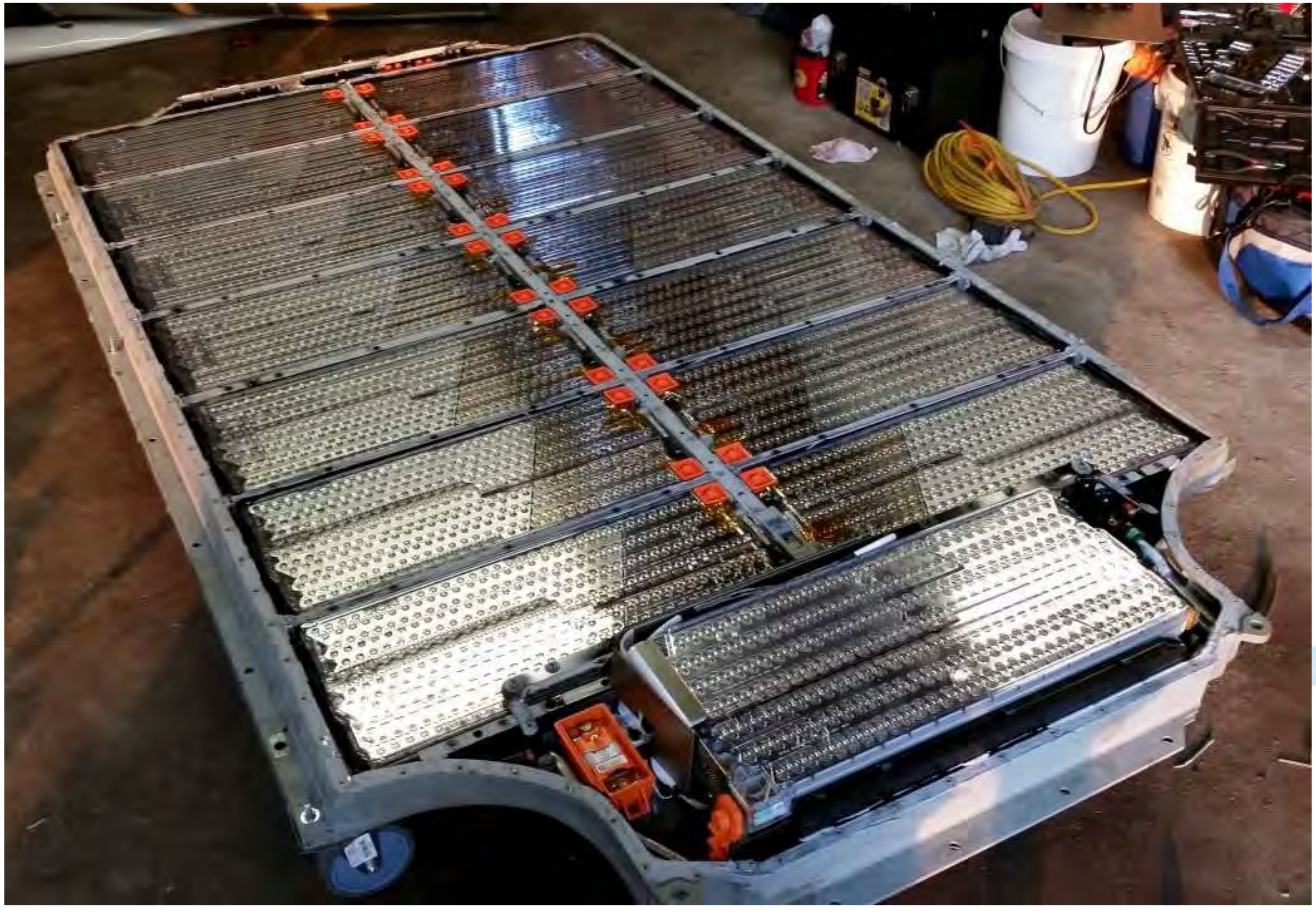
12S/1P Volt (12 Pouch Cells)

12S/2P EnerDel Module
(24 Pouch Cells)

2S/2P Leaf Module
(4 Pouch Cells)

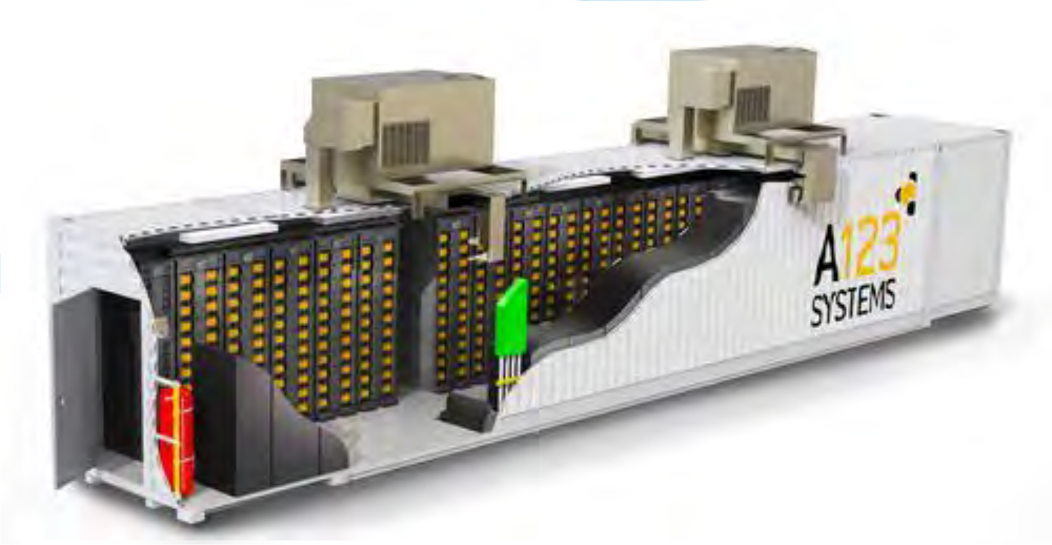
4S/9P Brammo Module
(36 Pouch Cells)

Battery Pack Examples



Battery Pack Examples

Battery Pack Examples



Battery Pack Considerations

BATTERY INNOVATION CENTER

Stationary/Grid

- The System is typically designed for the application, like for energy or power exclusively
  - **BUT, the cell often is NOT fully designed to application**
- Safety guidelines exist, but still evolving
  - UL, AVDE, IEEE
- Commonly modules are configured into catalog enclosures
  - Allow for common architecture
  - UL/NEC enclosure, sever racks, or shipping containers
- Environment is typically well regulated or calculated
- Typically not space constrained
- **KEY METRIC: Long Life, low cost**

Risk: Thermal Runaway

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- **Battery Safety & Standards**
- Ideal Applications Today
- Market Growth: Past, Present, and Future

Identifying and Addressing Hazards

BATTERY INNOVATION CENTER

- Fire
- Arc flash
- Explosion
- Reaction

Energy

- Electric shock
- EMC
- ESD
- EMI
- Connections

Electrical

- Pressure
- Noise
- Moving parts
- Integrity

Mechanical

- Toxic and hazardous substance exposure
- Interactions

Chemical

- Communication
- Validation
- Commissioning
- Site/Locating
- Cybersecurity

Control and Installation

Standards Bodies

- UL (Underwriters Laboratories)
- IEC (International Electrotechnical Commission)
- IEEE (Institute of Electrical and Electronic Engineers)
- ISO (International Organization for Standardization)
- UN
- CSA Group (Canadian Standards Association)
- SAE (Society of Automotive Engineers)
- CEN (European Committee for Standardization)
- ANSI (American National Standards Institute)
- ASME (American Society of Mechanical Engineers)
- ASTM (American Section of the International Association for Testing Materials)

Standards

- **UL** (Underwriters Laboratories)
  - Standards for Safety for North American countries
  - *UL 2580* – Batteries for use in Electric Vehicles (System)
  - *UL 1642* – Standard for Safety (Lithium Ion Cells)
- **IEC** (International Electrotechnical Commission)
  - Standards for energy production, transmission, semiconductors
  - *IEC 62133* – International Standard for Secondary Cells/Batteries (Alkaline or non-acid electrolytes)
    - Forced Internal Short Circuit
- **SAE** (Society of Automotive Engineering)
  - Aerospace, Commercial Vehicle, and Automotive Standards
  - *SAE J2464* – Electric/Hybrid Vehicle Safety and Abuse Testing
- **USABC** (United States Advanced Battery Consortium)
  - Standards for batteries in US EVs
  - *Electric Vehicles Battery Test Procedures Manual*
  - *USABC Abuse Test Procedures Manual*

UN DOT 38.3: Testing for Lithium Battery Transportation

- Methods for Cells, Batteries, Component Cells
  - T1: Altitude Simulation: Simulates air transport under low-pressure
  - T2: Thermal Test: Assesses seal integrity and internal connections
  - T3: Vibration: Simulates vibration during transportation
  - T4: Shock: Simulates impacts during transportation
  - T5: External Short Test: Simulates external short circuit
  - T6: Crush/Impact: Abuse that may result in an internal short circuit.
  - T7: Overcharge: Ability of battery to withstand overcharge condition
  - T8: Forced Discharge: Ability of battery to withstand discharge condition

Can be offered with a UL Type Certificate in addition to completed test datasheets.

UL 1973: Batteries for Use in Light Electric Rail (LER) and Stationary Applications

- **Non-Technology Specific**
  - Lead-Acid, Nickel, Sodium Beta, Lithium ion, Flow Batteries, Electrochemical Capacitors and Battery/Capacitor hybrid systems
- **Safety Analysis**
  - Single Fault Conditions
  - FMEA, FTA
- **Construction Requirements and Tests**
  - Materials, Enclosure, Electrical, Safety Controls, Cells, Environmental/EHS, Markings

UL 9540: Energy Storage Systems and Equipment

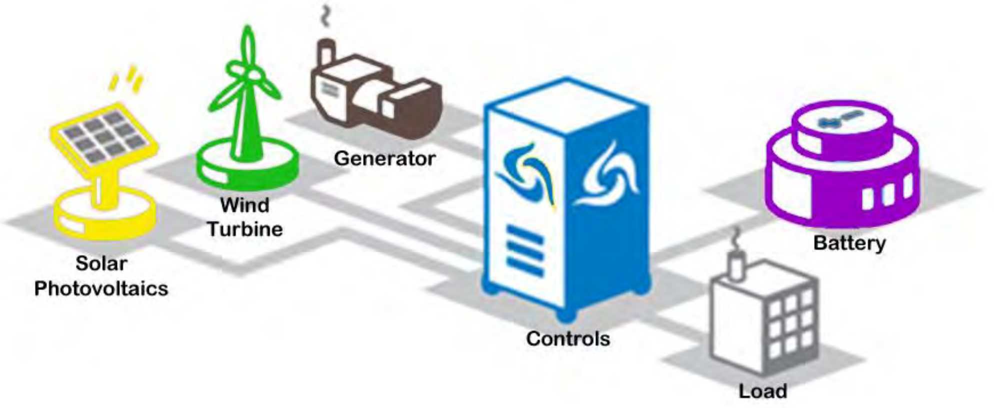
- **Includes the following Energy Storage Systems**
  - Standalone to provide energy for local loads
  - In parallel with an electric power system, electric utility grid
  - Able to perform multiple operational modes
  - For use in utility-interactive applications in compliance with IEEE 1547 and IEEE 1547.1
  - Other applications intended to provide grid support functionality,
  - May include balance of plant and other ancillary equipment of the system
- **Utility Grid Requirements and Tests**
  - Must Operate safely through various conditions
  - Enclosures
  - Electrical
  - Fire Detection and Suppression
  - Markings/Signage

NEC 2017 has 3 new articles all requiring listing to UL 9540.

It's expected OSHA will also add this to their standards list and require certification from a NRTL.

Communication Standards: OpenFMB

- **Open Field Message Bus (OpenFMB) Standard**
  - Think "USB/Plug and Play" for the Energy Storage market
  - Proposed interoperability test standard
  - Establishing a non-proprietary set of specifications and protocols for energy storage under a consortium of electric utilities and technology suppliers
  - Addressing how energy storage components are packaged and arranged, electrically connected, and able to communicate with each other and other operational components
- **Micro-Grid Cybersecurity: Evolving Standard(s)**
  - Cyber parameters for residential through community level ESS's
  - Hardware resiliency and redundancy
  - Build upon existing software protection
  - Exploring compatibility with legacy controls



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- **Ideal Applications Today**
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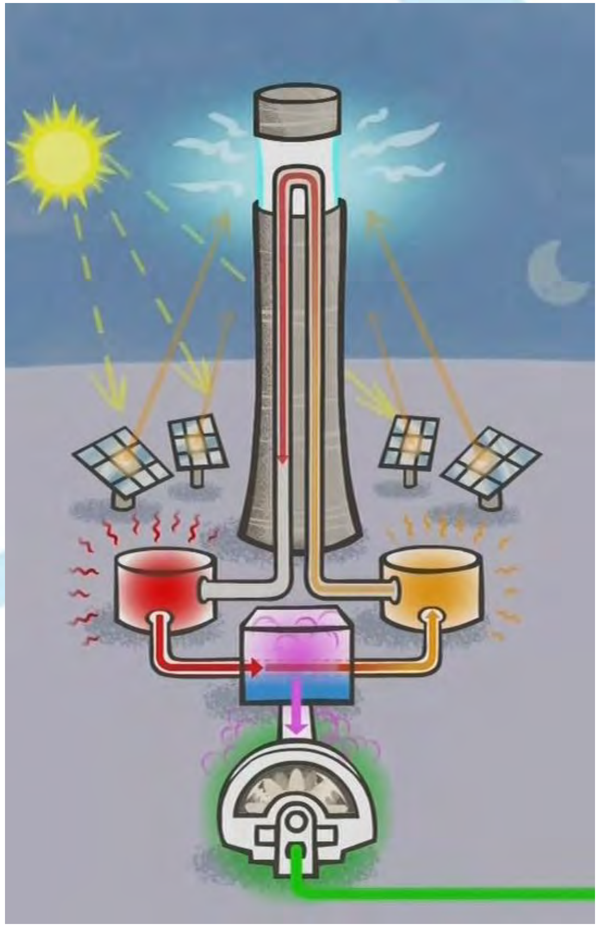
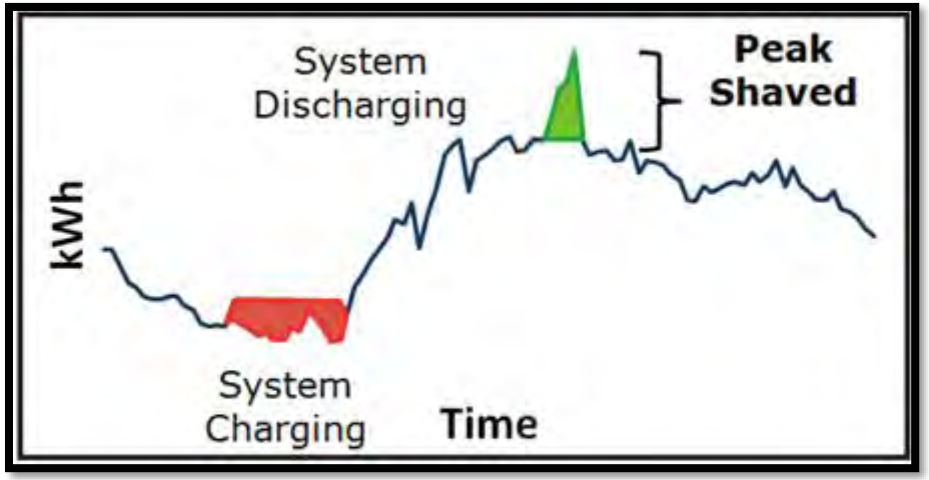
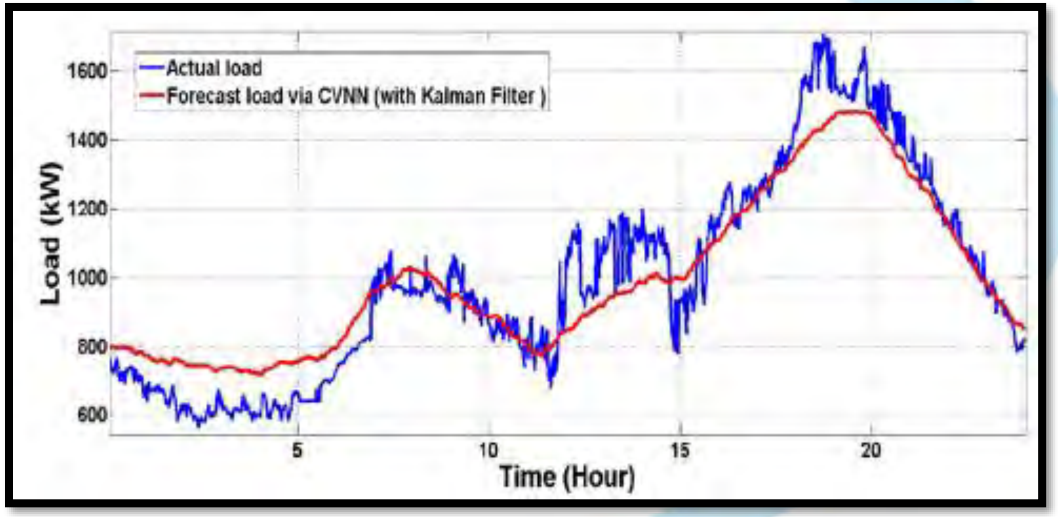
Applications for Grid Energy Storage

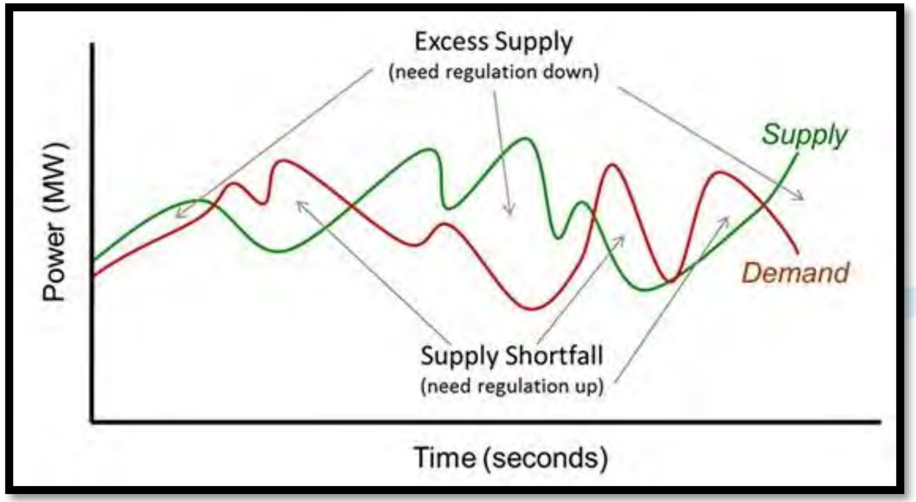
- **Fast response time to load, balanced with energy density and efficiency, is key to effective application**
- Peak Shaving, Power Smoothing, Frequency Regulation, Load Shifting
- **Silent**

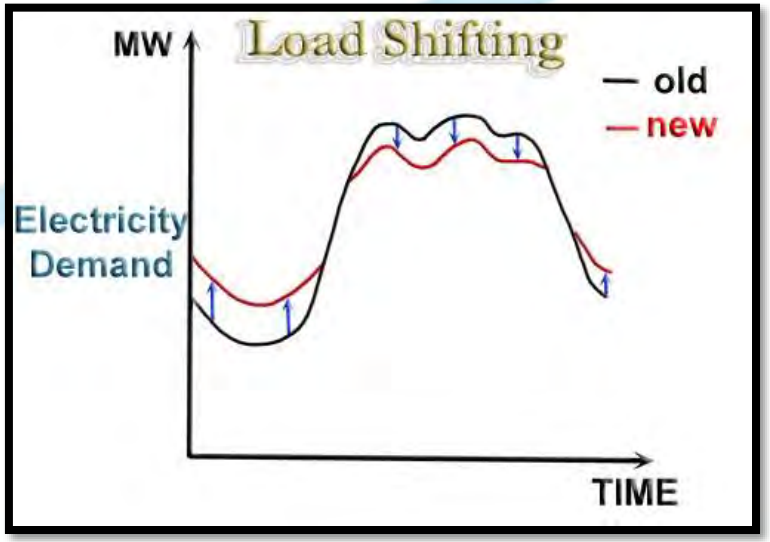


Peak Shaving, Power Smoothing, Frequency Regulation, Load Shifting



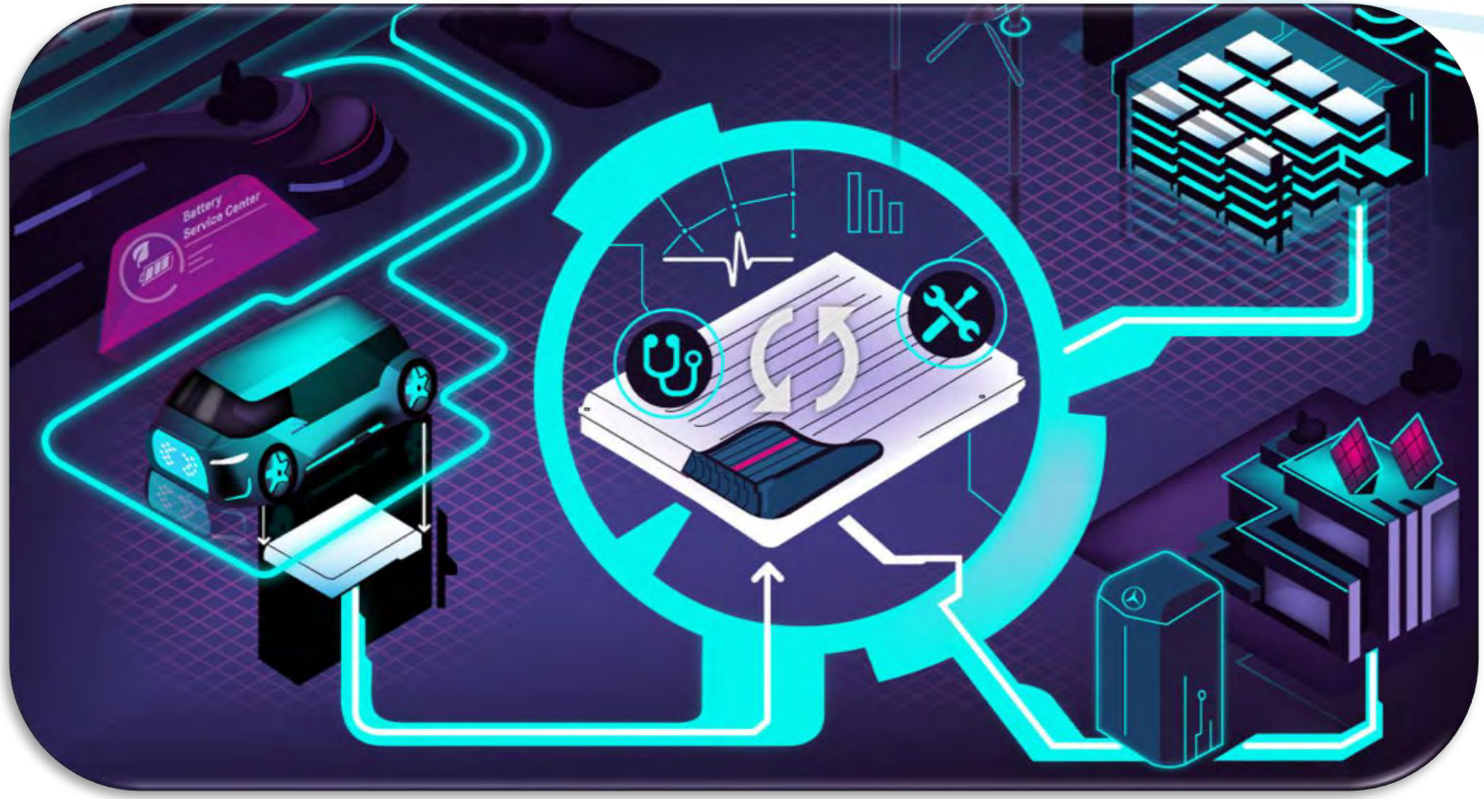






Typical Applications of Grid Energy Storage Systems

- **Pb-Acid (Battery)**
  - High power, short duration (<15 min) UPS, Load leveling
- **Li-Ion & Sodium Sulfur (Battery)**
  - Daily cycling for peak shaving, storage for renewables
- **Vanadium Flow (Battery)**
  - Long lasting UPS (days) for remote areas
- **Capacitors / Supercapacitors / Ultracapacitors**
  - Extreme pulse power, power quality, frequency regulation
- **Compressed Air & Pumped Hydro**
  - Energy storage of coal, nuclear, solar, or wind during off peak hours
- **Flywheel**
  - Quick response load leveling and frequency regulation, power transition to generator after power loss
- **Thermal**
  - Storage for solar (molten salt daily cycle), reselling energy



50kWhr/EV @ 1M = 50 GWhr

Global Battery Production:

2017: 40 GWhr

2018: 72 GWhr

Battery End of Life to 2nd Life

What happens 10+ years after 1M+ EV/yr sales?

2nd Life vs Remanufacturing

- 2nd Life – Existing product that is repaired or used for a new application.
  - – No changes made to the battery
  - – Batteries at 80% utilized for non-mobile applications
  - – Additional batteries combined to hit energy/power requirements
  - – Aftermarket “Lower Grade” batteries sold for shorter use applications
- Remanufacturing – Existing product is deconstructed and re-built
  - – Pack remanufacturing
    - Requires good modules
  - – Cell remanufacturing
    - Requires good materials

Second-Life: In Practice

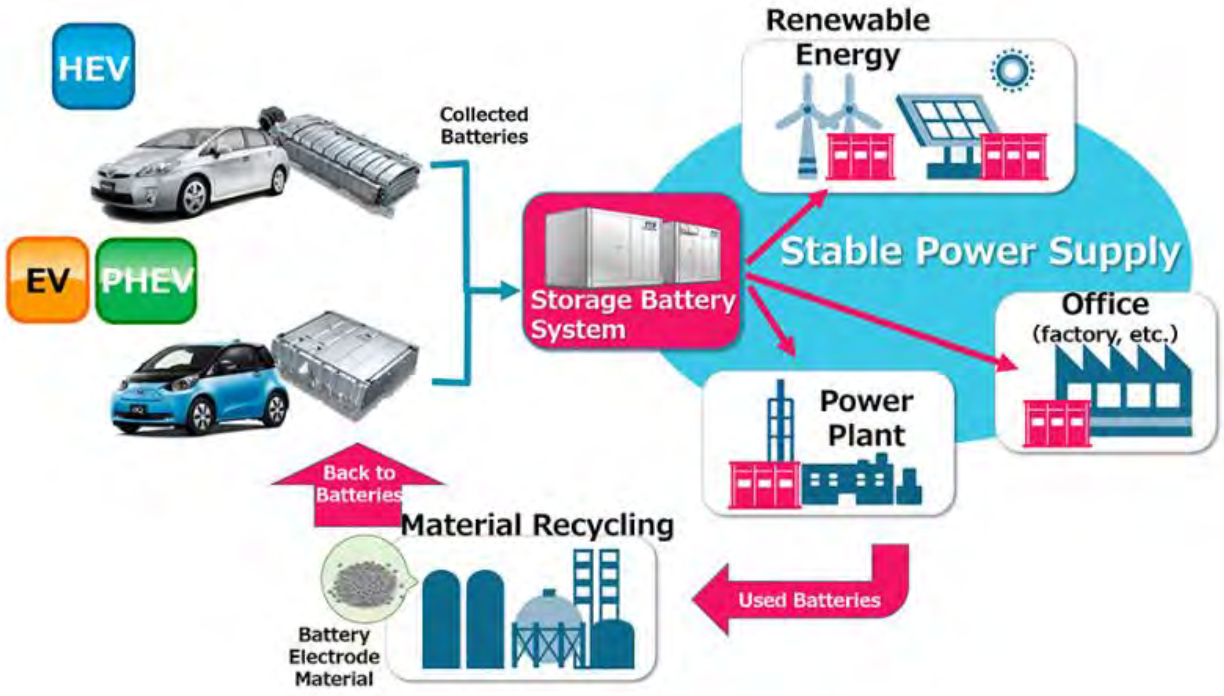
19 Jul, 2018:

EVgo in Union City, CA installs 2 BMW i3 batteries (22kWh each) donated by BMW into a charging station to help offset peak demand and store excess solar energy.

17 Jul, 2018:

Audi using 84 batteries in 2nd life application for a 1MWh load shifting and frequency regulation application in Nuremberg Germany.

Second-Life: In Practice



31 Jan, 2018:

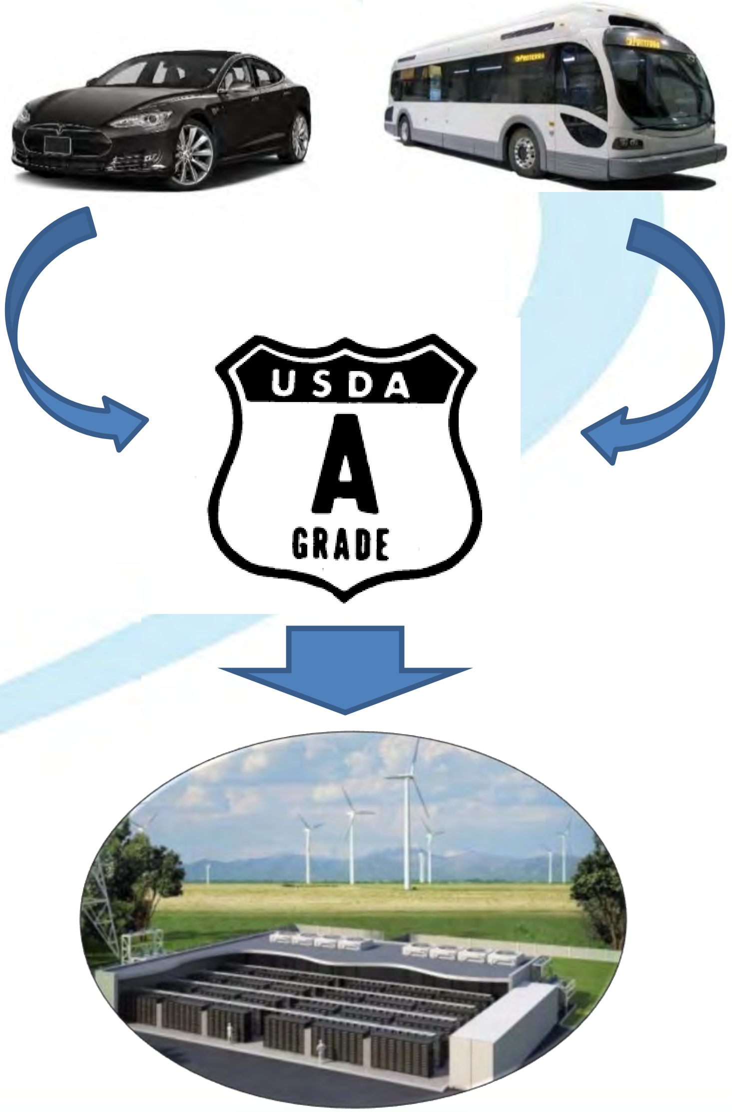
Chubu Electric Power (Nagoya City, Japan) announced agreement with Toyota regarding a large capacity storage battery comprised of NMH EV batteries for energy supply-demand adjustment and suppression of grid voltage fluctuations caused by renewable energy sources. Initial goal is to have 10MW capability online by 2020 with plans to use Li Ion EV batteries by 2030.

Second-Life: In Practice

- **May2018:** Nissan Japan offers Leaf owners a refurbished battery for an exchange with a cost of $2,853 vs. the $6,182 cost of a new replacement battery.
- **Nissan:** entering joint venture for 2nd life uses with a 4R business model (Reuse, Resell, Refabricate, Recycle) in both Japan and the US.
- **Oct2018:** Nissan and EDF Energy (UK) start pilot program for 2nd Life Leaf batteries in demand response application

Second-Life: Opportunities

- **The cost of “Total Life” can be spread to more users**
  - Lower the overall cost to industry
  - Core/exchange model is well supported in the automotive industry
- **Certification/Validation**
  - UL, IEC, and others are setting up for multi-certification
    - Cost sharing during PV and cert.
    - Streamlining 2nd life introduction
- **Expanded applications for batteries**
  - Previously cost prohibitive
  - Low-cost regions consideration
- **Partnerships between industries**
  - Pre-arranged applications
  - Shared cost potential



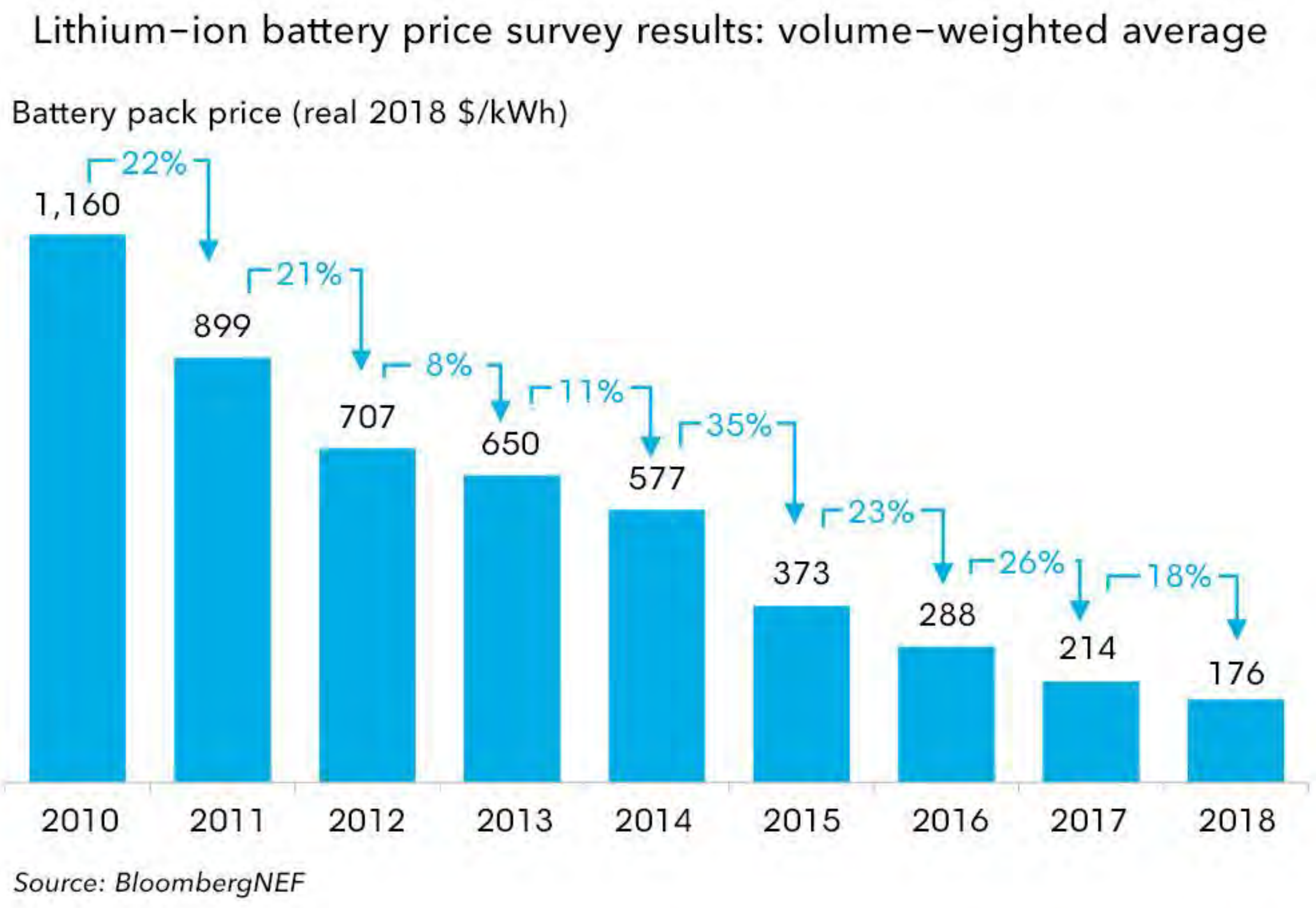
Second-Life: Challenges

- 2^{nd} Life Supply chain is still not fully established (However it is quickly evolving)
- Market is not mature for second use batteries
- Institutional roadblocks
- No standard grading system
- Regulations
    - Take back law
    - Transportation laws
- Continued decrease in $ of new batteries

Outline

- Energy Storage Technology Landscape
- Batteries 101
- Battery Safety & Standards
- Ideal Applications Today
- Market Growth: Past, Present, and Future

It May Not Be Moore's Law, but…



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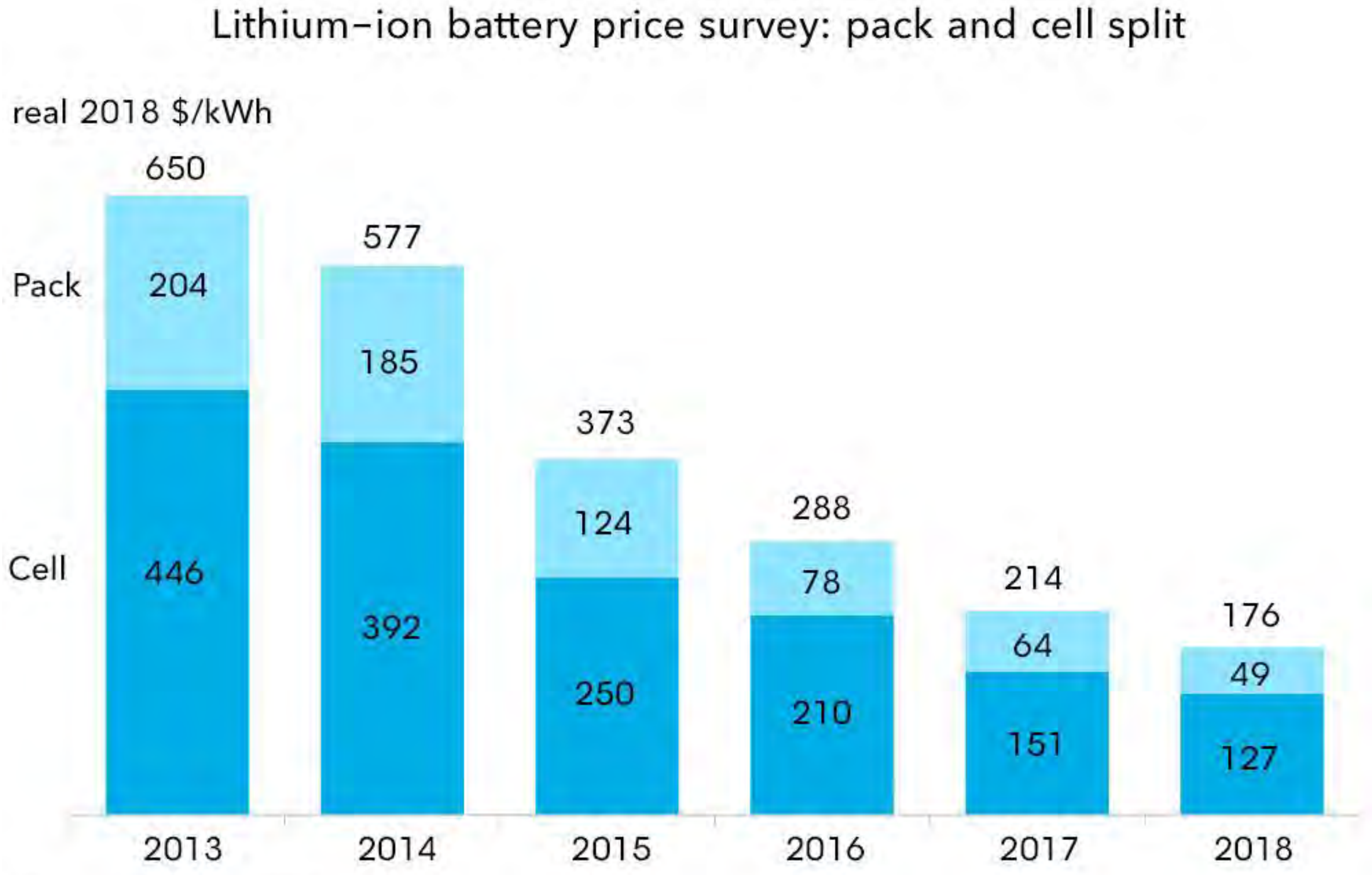
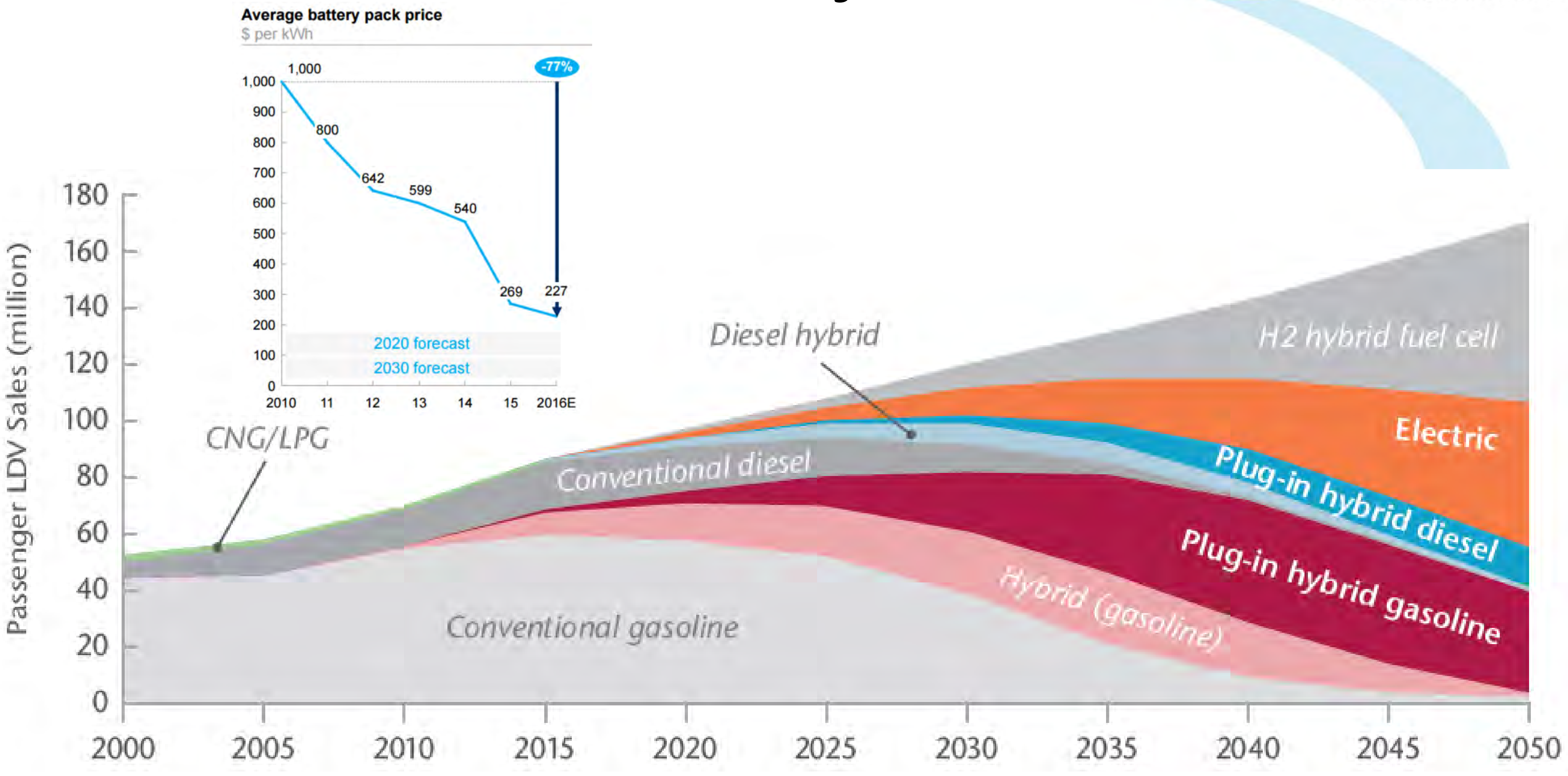


Source: BloombergNEF

Electric Vehicle Sales Projections

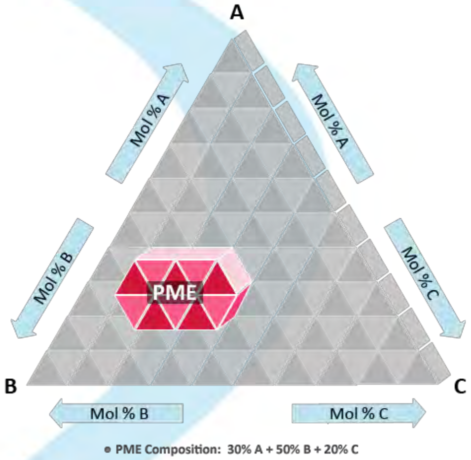


Dark Horse: Solid / Semi-Solid Electrolytes

BIC
BATTERY INNOVATION CENTER

- Eliminates separator
- Improves safety
- Increases voltage range
- May enable high cycle life in conversion chemistries
- May involve new formats or processing
  - It's all about the interfaces, not bulk ionic conductivity!

BRIGHTVOLT
SMALL POWERED SOLUTIONS



Solid Power
BMW
Hyundai

QuantumScape
VW

solid energy
GM

TOYOTA
Concept EV 2020

Prieto Battery
Intel

SAKTI3
Dyson

ionic MATERIALS
Renault, Nissan, Mitsubishi

A123 Purchased - EV 2023

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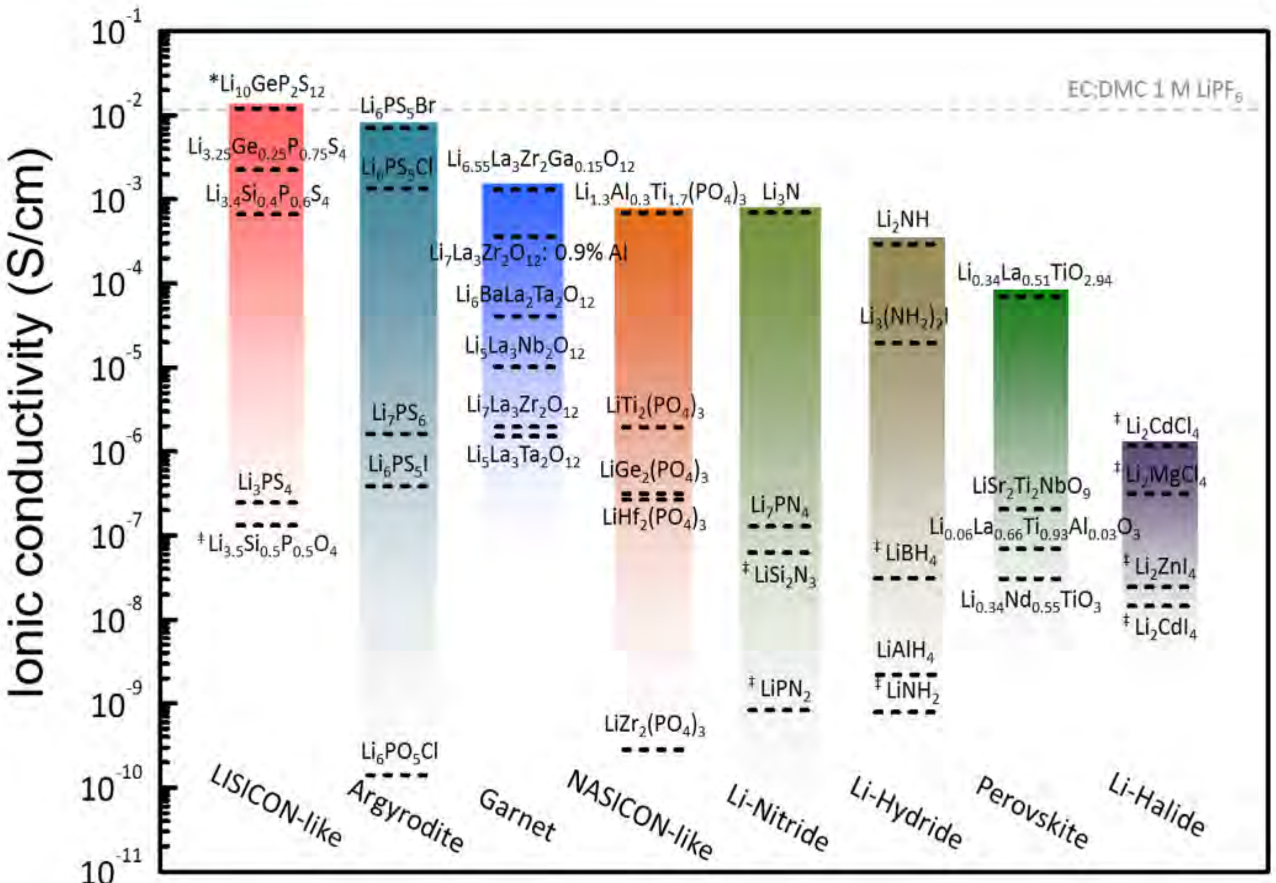
Reported Total Ionic Conductivities of Solid Electrolytes



Bachman (2016) - https://dspace.mit.edu/handle/1721.1/109539

100,000 ft View: Ongoing Advances

BIC BATTERY INNOVATION CENTER

Cell Technology Perspective (~$125/kWhr)

- Conversion based chemistries will grow in market share
- Hybrid to full solid electrolyte batteries are close to making an impact, but likely in electronics before EV
- Cells will continue to integrate more nanostructured features and manufacturing techniques must adapt
- Decreasing variance in current density (A/m^2) and electric field strength (V/m) in cells (Increased quality, consistency, performance profiles, & lifetime)

Pack Technology Perspective (~$175/kWhr)

- Thermal management design varies widely now, but will converge on optimized designs
- Battery management systems to grow more sophisticated
- **Basic manufacturing improvements and economies of scale will continue for the foreseeable future**

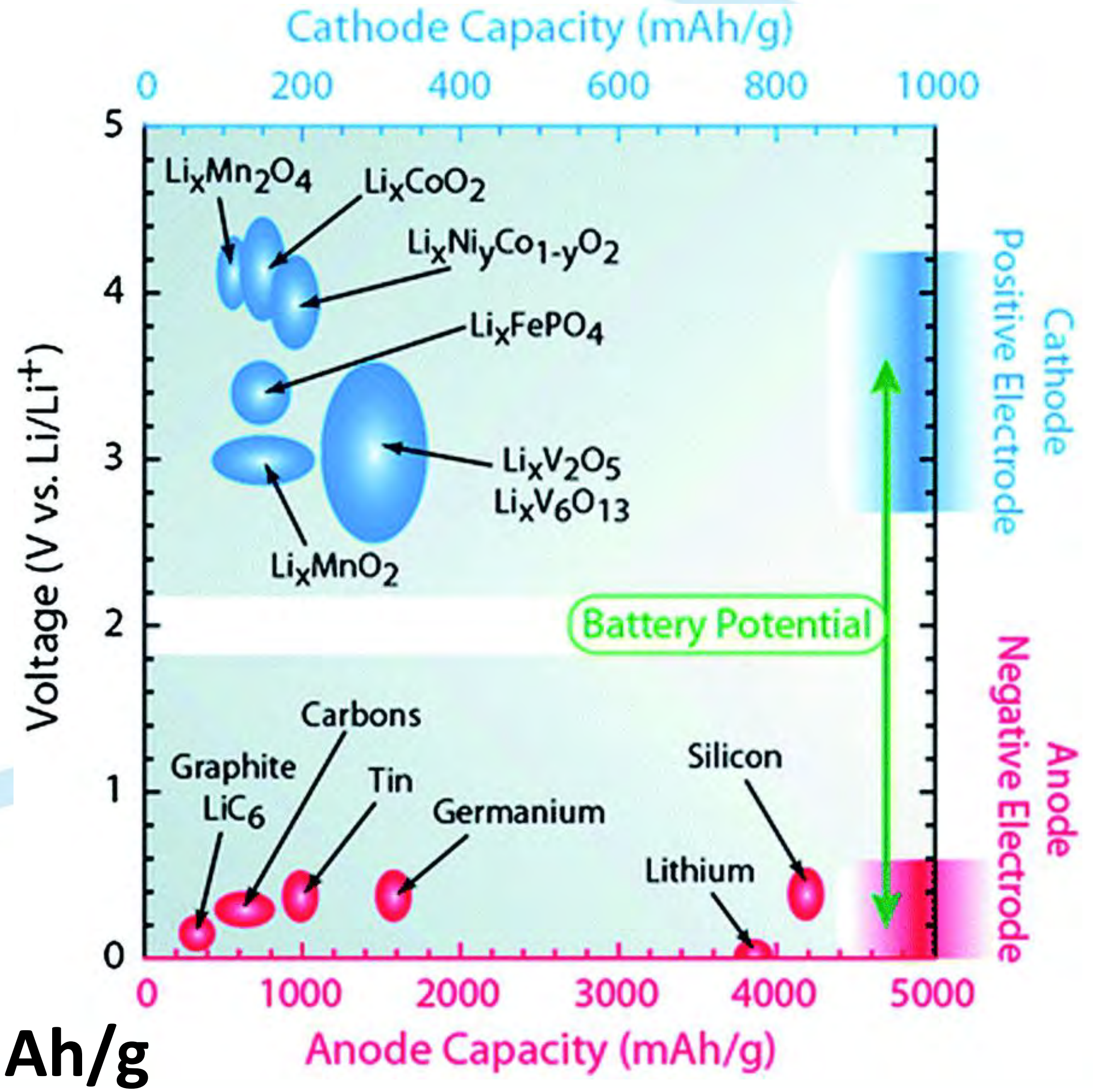
Thank You

BIC
BATTERY INNOVATION CENTER

- UL
- Purdue University
- NAVSEA Naval Sea Systems Command
- Saft
- Rolls Royce
- Ten Nine Tech
- Sillion
- Radius Indiana – Igniting Prosperity in the Heart of Southern Indiana
- MTD For A Growing World.
- Vectren Live Smart
- IU
- Chroma Systems Solutions
- AV aerovironment
- EaglePicher Technologies, LLC
- Canada NRC·CNRC
- MEGTEC
- BrightVolt Small Powered Solutions
- Black Diamond Structures
- NEC
- Maccor
- NextFlex America's Flexible Hybrid Electronics Manufacturing Institute
- Nexceris where energy meets environment
- MESA Open Standards for Energy Storage
- SAIC From Science to Solutions
- SunSpec Alliance
- inmatech
- EtaVision get the most out of your infrastructure investments
- Duke Energy
- pellion technologies
- enerG2 Next Generation Energy Storage
- SiNode Systems
- 1energy Systems
- EastPenn
- Fisker
- ESN Energy Systems Network
- ChargeCCCV
- A123 Systems
- Purcell Systems an EnerSys company
- Georgia Tech
- سابك sabic
- Albemarle
- Gexpro
- Cummins
- ISOtunes
- Vincennes University
- LG Chem
- Leclanché
- Ultra Electronics
- Stealth Power
- Indiana iot Lab Fishers
- glassboard Product Development
- ipl an AES company
- Eclipse Energy Labs testing, analysis, energy IQ
- Lynntech

Mechanisms of Operations

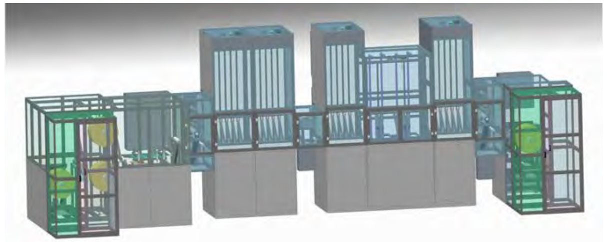
- Potential (Voltage)
  - The amount of electrochemical potential energy between the exchange of charge in a reaction
- Charge Transfer (**$Li \leftrightarrow Li^+ + e^-$**)
  - Versions exist at every interface and tend to be the fundamental rate limiting step
- Diffusion
- Intercalation
  - The reversible insertion of Li^+ between the lattice sites of the active materials
  - **$6C + Li^+ + e^- \leftrightarrow LiC_6 \Rightarrow 372$ mAh/g**
- Conversion / Alloying
  - The reversible generation of a new structure incorporating the reactants
  - **$5Si + 22Li^+ + 22e^- \leftrightarrow Li_{22}Si_5 \Rightarrow 4200$ mAh/g**

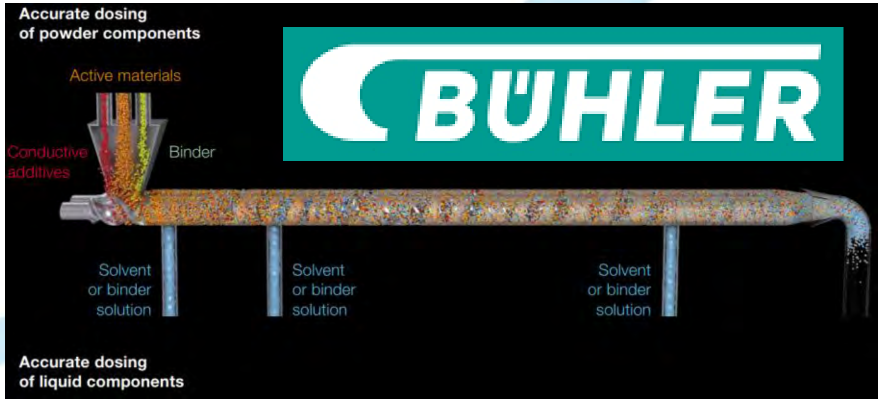


Manufacturing Methods (still in the 1980s)

- Move towards improved consistency and symmetry
- Strong interest in alternative coating processes, when economies can be proven
- Continuous processing (vs. batch!!!)
  - Mixing → Coating → Drying → Calendering → Slitting - - -→Pre-lithiation?
- Process monitoring
  - Passive
  - Active

Nanoscale Components





Buhler continuous mixing process for electrode production

B&W Gigacoater – Roll to Roll 3 GHr/yr simultaneous double sided coater-dryer

Battery Management System (BMS)

Monitoring
- Voltage
- Temperature
- Current

Calculation
- Charge/Discharge Limits
- Internal Resistance/Impedance (IR)
- Cycle Count/Time

Balancing
- Passive
- Active

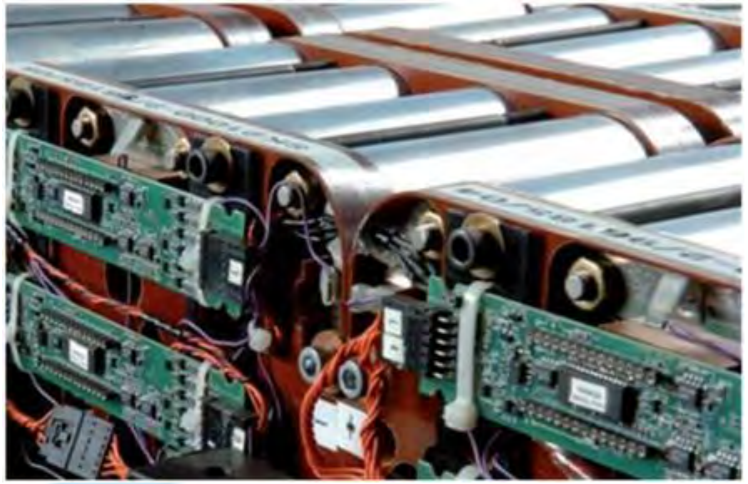
States
- State of Charge (SOC)
- State of Health (SOH)
- State of Function (SOF)

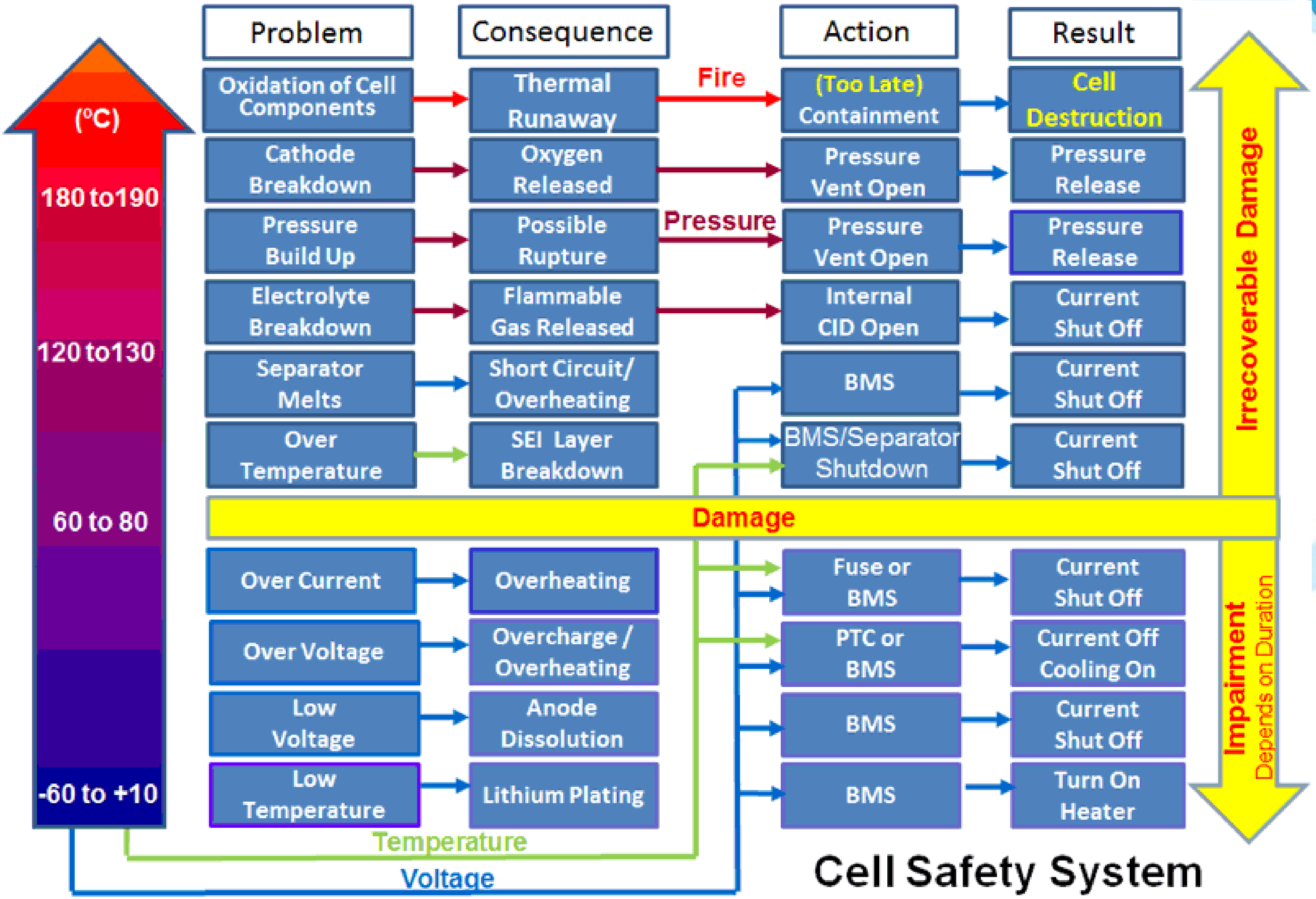
Communication
- Serial and CAN
- Wireless

Control
- Protection
- Operation

Architecture
- Centralized
- Distributed

  +(Hybrid)





Cell Safety System

2019 Overview

Rev 1.2

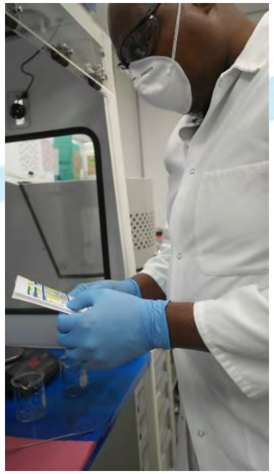
Advanced Cell Manufacturing

Low Volume Cell and Pack Production

- <1% Humidity Dry Rooms & 10,000 Class Clean Rooms
- Commercial quality cell manufacturing equipment
- Support of multiple cell formats including Cylindrical, Pouch, Prismatic, & Coin-cell
- Proof of Commercialization expertise
- Pack design and assembly equipment

R&D Material and Process Development

- PhD materials scientist and research engineers
- Advanced use of industry leading materials and cutting edge technologies
- Small batch mix and coat capabilities
- Direct partnerships with industry suppliers
- Factory demo center for equipment OEMs



Test and Validation

Battery Testing and Evaluation

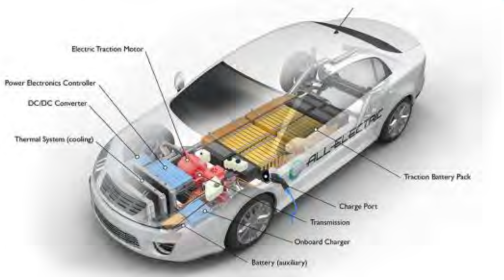
- Full suite of T&E equipment for single cells up to complete systems of 1MW+
- 160+ channels of cell cycling
- Multiple altitude, humidity, and thermal environmental chambers
- Two 1200ft^2 controlled labs for EHS level tests
- Large Format Forced Internal Short Circuit
- Crush, Propagation, Drop, External Fire, and more
- Outdoor testing capabilities
- Access to NSWC Crane Testing Capabilities
- Industry certification to UL, MIL, UN-DOT, SAE, IEEE standards

Micro-Grid Systems Testing

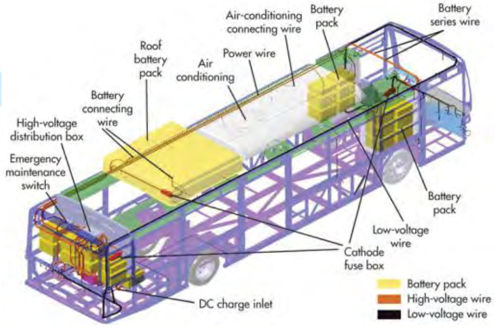
- AC utility-scale grid simulators (180kW+ scalable)
- Integrated solar and wind renewables
- 5 residential, community, and grid ESSs on-site
- Facility is connected to >6MW of available power with net metering (MISO High Voltage Node) agreement
- Configured to allow plug-n-play of multiple versions of ESSs, inverters, PCSs
- Cybersecurity Program-Hackathon

Applied Research & Consulting

- Professional Feedback and Analysis
  - Facility Processes and Design
  - Industry Best Practices
  - Safety Analysis and Auditing
  - Battery Management Systems (BMS)
  - Module, Pack, and System Design
    - Grid
    - Electric Vehicles
    - Consumer Electronics
    - Drones
    - IoT



- Competitive Analysis
  - Test Equipment
  - Manufacturing Equipment
  - Cells, Modules, Packs, and Systems
  - Battery Components
  - Software
  - Cell Dissection and Lab Analysis



Education Programs

- **Battery Short Course (CE Credits):** 3-4 Day Session
  - In-depth outline: Chemistry, BMS, Module/Pack/System Design, Manufacturing, Validation, T&E, Cybersecurity, Field Service, Warranty
  - Gain a deep, broad, and well-rounded understanding of the current industry
  - Open classes offered quarterly
  - Private customized courses now also being offered

- **AC/DC HV Fundamentals Course (CE Credits):** 2 Day Session
  - High-Voltage training for all personnel involved with energy storage systems and components
  - Covers the history, base-line fundamentals, industry best practices, PPE, and technology considerations

- **Energy Storage Technologies Executive Workshop:** 1 Day Session
  - Provide foundational knowledge and in-depth discussion
  - Focus on ESS technology, motive, and grid-related applications
  - Accepting reservations now for on-going classes

- **On-Site Training:** Customized for You
  - We bring the industry expertise to your door
  - Dedicated and comprehensive single-topic courses on emerging technology

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Strategic Alliances

- UL BEST (Battery and Energy Storage Technology) exclusive large-format ESS test facility
  - On-site UL experts combined with BIC capabilities
  - ISO 17025 accreditation in process
  - One-stop direct collaboration with UL and BIC
  - Industry-trusted certification and validation

- BrightVolt selected BIC as their scale up location for Ultra-Thin Film, Flexible Batteries
  - Expanding operations at the BIC
  - R&D initial focus, with pilot-production scale up capabilities
  - Helping to commercialize battery technology for medical patches, industrial sensors, IoT devices, shipping labels, and smart card technologies.

- Duke Energy platform for micro-grid simulation and grid-level control algorithm development
  - Micro-Grid environment with full infrastructure to evaluate grid components
  - 5 complete and diverse sets of ESS + Inverter + Software
  - 1MW direct-tie grid inverter
  - Leveraging installed and new renewable generation
  - Communication development using emerging MESA and SunSpec standards

- NAVSEA-CRANE CITE agreement allows direct access to the Navy's world-class EHS test facilities
  - Among the broadest Test & Evaluation capabilities in the U.S., if not the world
  - Crush, shock, drop, vibe, rapid disassembly, intrusion, EMI, among others
  - BIC/UL employees perform testing while utilizing NSWC facilities